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Simulation of moist convective boundary layers with eddy-diffusivity/mass-flux parameterization

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Motivation

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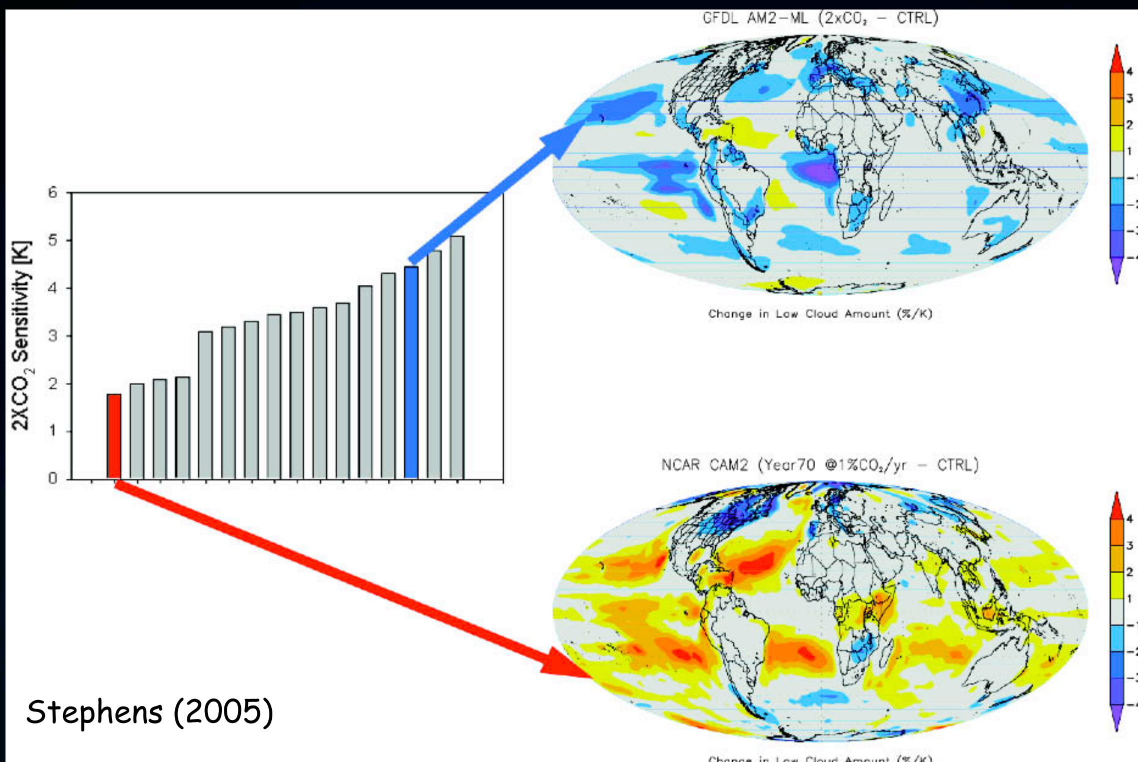
Improving PBL parameterization in convective boundary layers:

- GCM climate response highly dependent on low level cloud extend

IPCC (2007): 'Cloud feedbacks remain the largest source of uncertainty'



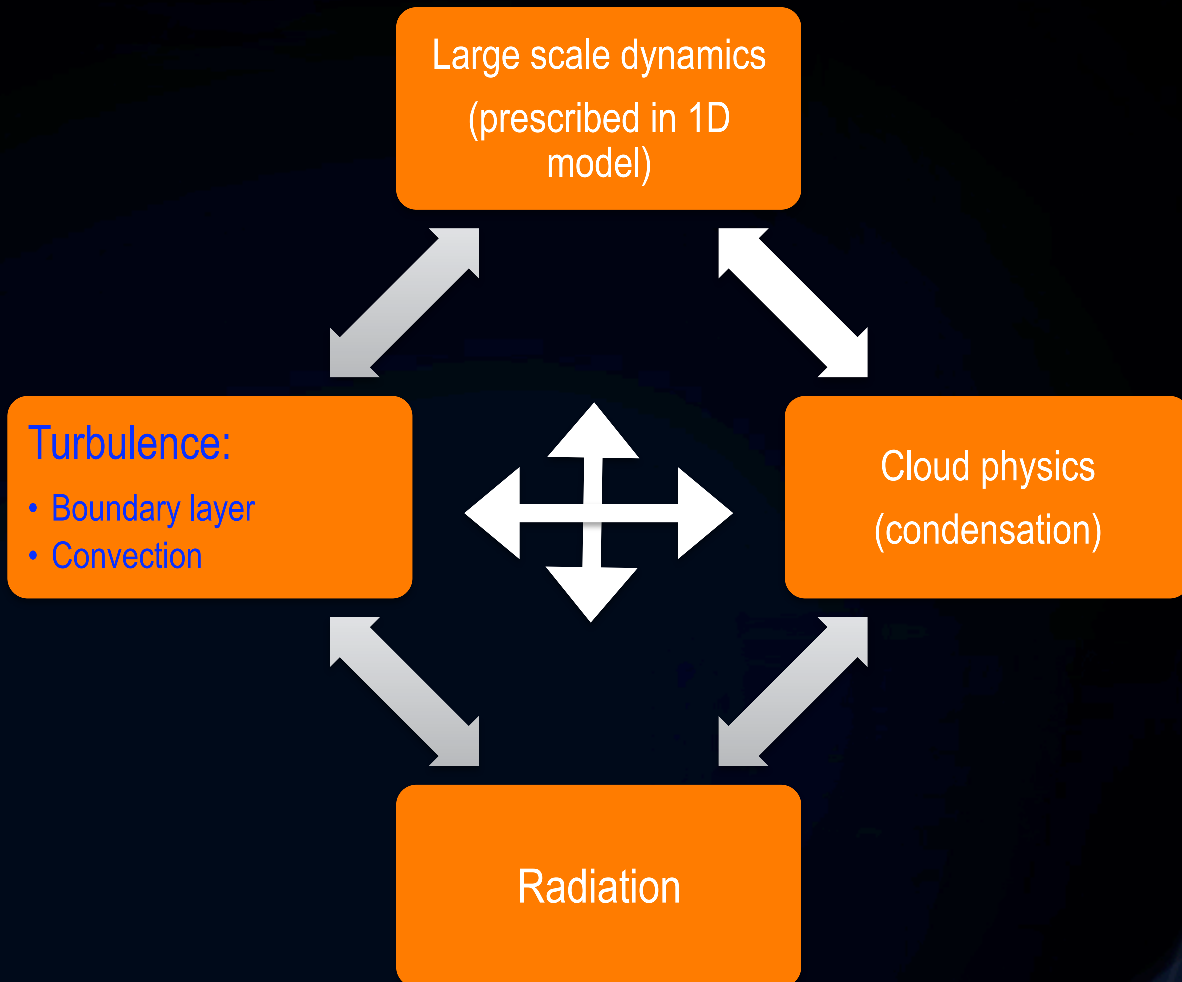
Stephens (2005)

Doubling CO_2 ➔ less low clouds in GFDL ➔ ≈4 K global warming

Low level cloudiness increases albedo

Doubling CO_2 ➔ more low clouds in NCAR ➔ ≈2 K global warming

Physical processes influencing low level cloud formation and breakup

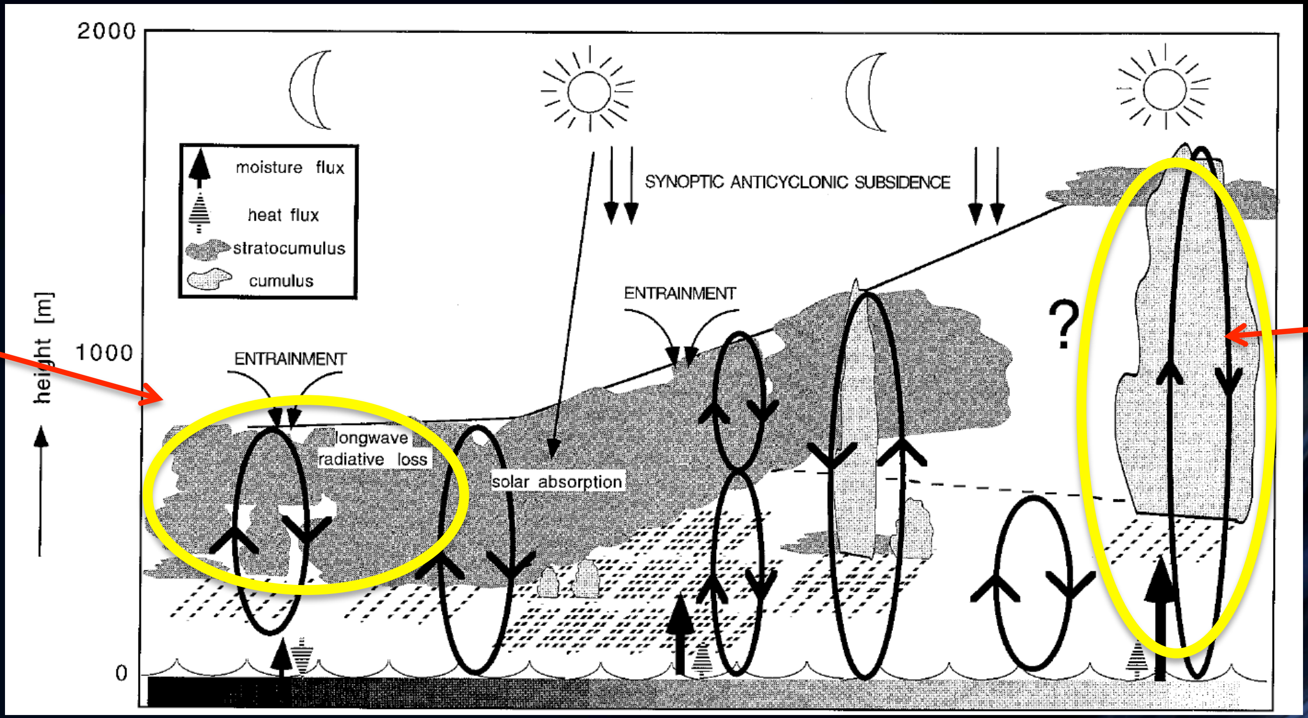


Approach for improving boundary layer parameterization

1. Developing and testing turbulent and cloud parameterization based on Eddy-Diffusivity/Mass-Flux (EDMF) approach in one-dimensional model:
   - stratocumulus topped boundary layer
   - cumulus convection
   - transition

Stratocumulus - DYCOMS
B. Stevens et al., (2005)

de Roode and Duynkerke (1997)



Shallow cumulus - BOMEX
P. Siebesma et al., (2003)

Evaluation of parameterization – comparison to LES results

1D model – model dynamics

Prognostic equations for large scale flow:

$$
\begin{aligned}
\frac{\partial \theta_L}{\partial t} &= -w\frac{\partial \theta_L}{\partial z} - \frac{\partial \overline{w'\theta_L'}}{\partial z} + S_\theta \\
\frac{\partial q_t}{\partial t} &= -w\frac{\partial q_t}{\partial z} - \frac{\partial \overline{w'q_t'}}{\partial z} \\
\frac{\partial u}{\partial t} &= -w\frac{\partial u}{\partial z} + f(v - v_g) - \frac{\partial \overline{w'u'}}{\partial z} \\
\frac{\partial v}{\partial t} &= -w\frac{\partial v}{\partial z} - f(u - u_g) - \frac{\partial \overline{w'v'}}{\partial z}
\end{aligned}
$$

$$\theta_L = \left(\theta - \frac{L_v}{c_p T} q_l\right)$$

$$q_t = q_l + q_v$$

Numerical scheme: semi-implicit, upwind differencing

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1D model - turbulent parameterization

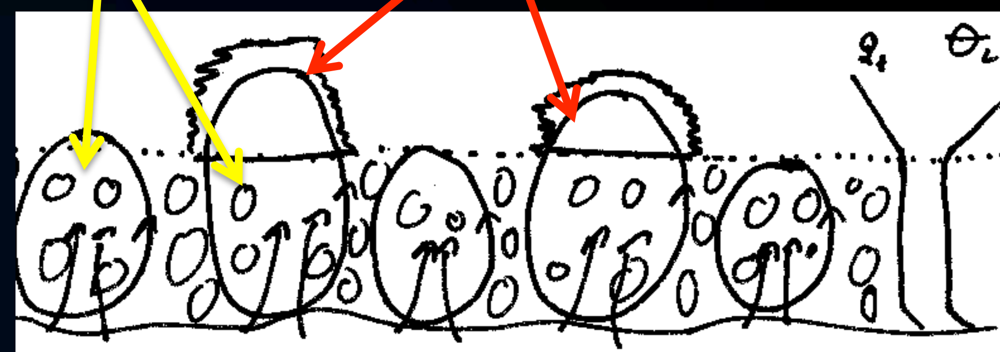
Parameterization of turbulent fluxes
- Combined Eddy diffusivity/Mass flux approach for scalars (Siebesma and Teixeira, 2000)
- Eddy diffusivity for momentum

$$\overline{w'\varphi'} = -K_H \frac{\partial \varphi}{\partial z} + \sum_i M_i \left(\varphi_{ui} - \varphi\right) \qquad \varphi = \theta_L, q_t$$

$$\overline{w'u_i'} = -K_M \frac{\partial u_i}{\partial z}$$

Eddy-diffusivity
(local mixing)

Moist updrafts -
cumulus clouds



Mass-flux transport
(strong buoyant updrafts)

Eddy-diffusivity scheme

$$K_{H,M} = C_{H,M}\, l \sqrt{e}$$

e - Turbulent kinetic energy (prognostic equation)
C_M, C_H - constants
l - mixing length:

$$l = f(kz; \tau\sqrt{e}; \frac{\sqrt{e}}{\tau N^2})$$

1D model – updraft parameterization

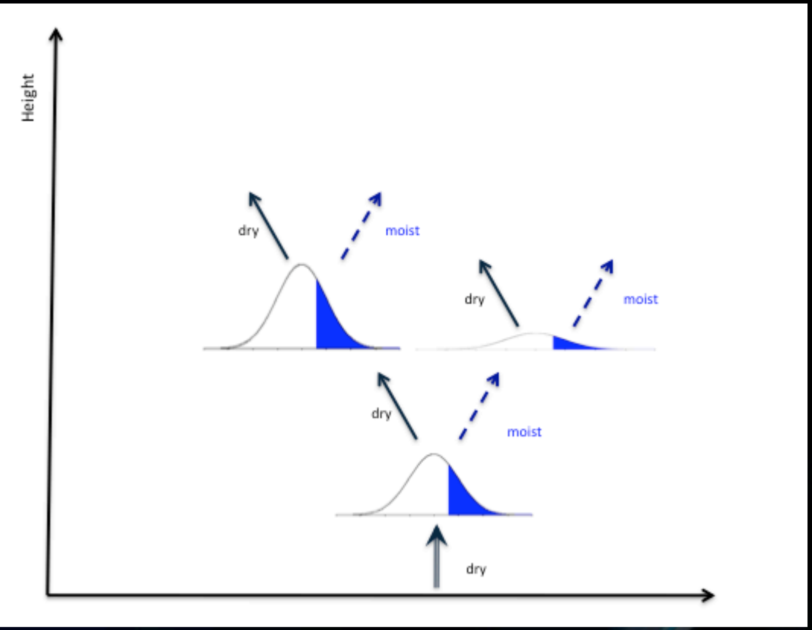
$$\overline{w'\varphi'} = -K_H \frac{\partial \varphi}{\partial z} + \sum_i M_i \left(\varphi_{ui} - \varphi\right) \qquad \varphi = \theta_L, q_t$$

Mass-flux scheme equations:

$$\begin{aligned} M_i &= a_{ci} w_i \\ w_i &= \frac{\partial w_i}{\partial z} - \epsilon \alpha w_i^2 + \beta B_i \\ \frac{\partial \varphi_{ui}}{\partial z} &= -\epsilon_i \left(\varphi_{ui} - \varphi\right) \end{aligned}$$

α, β – constants
$\varphi_u - \varphi$ (q_t or Θ_L) in updraft

a_c – Ratio of updraft area (0.1)
ε – Entrainment rate (diagnostic equation) $\alpha\ w^{-1}$
B – Buoyancy of the updraft

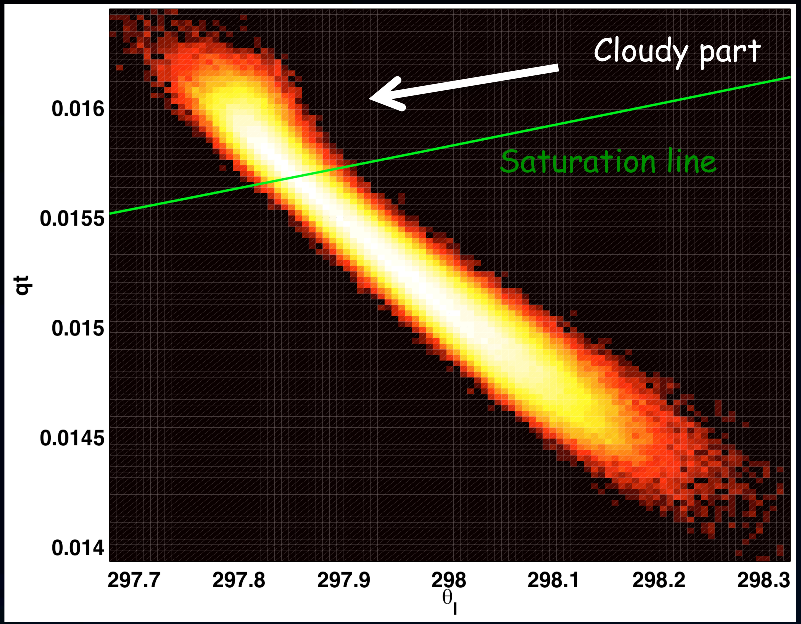


Condensation in updraft:

- Start with a single dry updraft at surface, integration in vertical
- Estimation of cloud cover and liquid water at each vertical level (pdf cloud scheme of Cheinet and Teixeira 2003)
- Separation of dry and dry updraft if condensation occurs, each of the updrafts is integrated independently

1D model – other physical parameterizations

Cloud physics – *pdf* scheme (e.g. Cheinet and Teixeira, 2003)



2D pdf of Θ_L [K] and q_T [kg/kg] at cloud base for shallow cumulus (RICO) case – from LES

Key for coupling between condensation and turbulence:

- Buoyancy flux
- Radiation (long-wave only)

Radiation Scheme – long-wave for cloudy layers only

- maximum cloud overlap
- emissivity based on liquid water content

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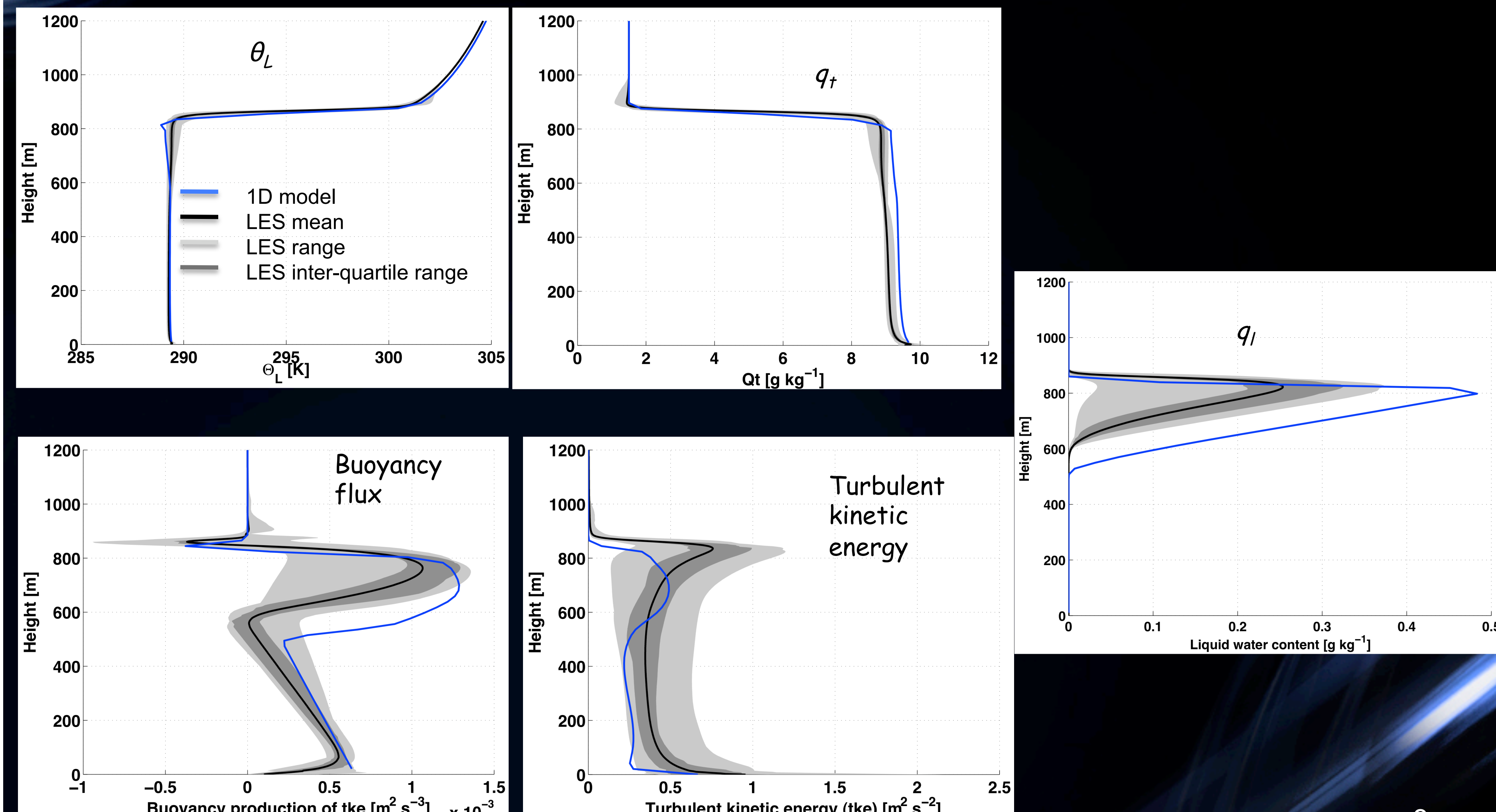
Results – Stratocumulus

Simulation of DYCOMS case, comparison with 16 LES results (Stevens et al., 2005)

- Mean profiles between 3rd and 4th simulation hour



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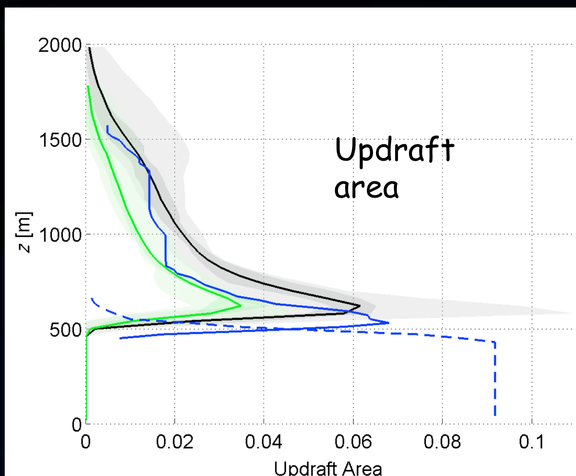
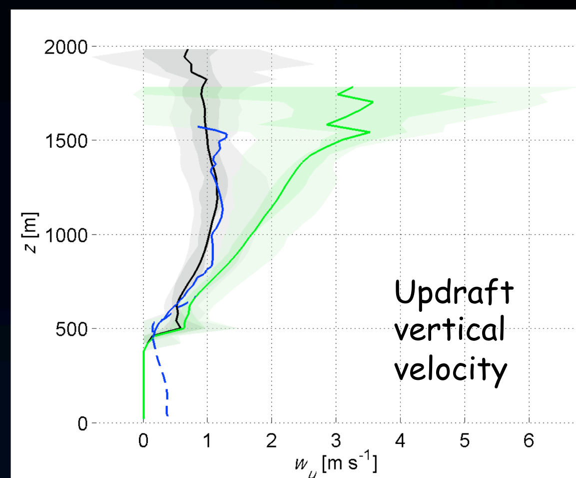
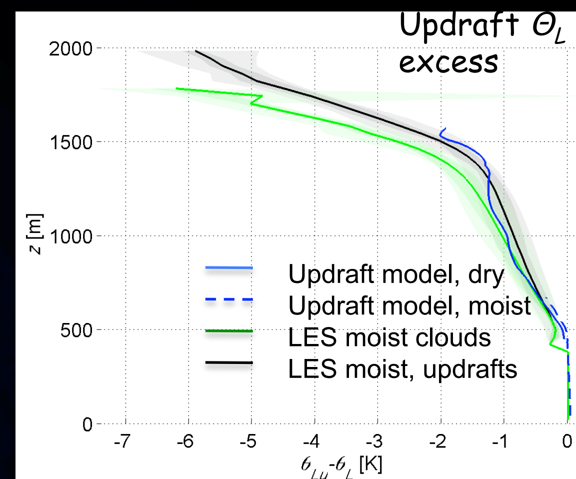
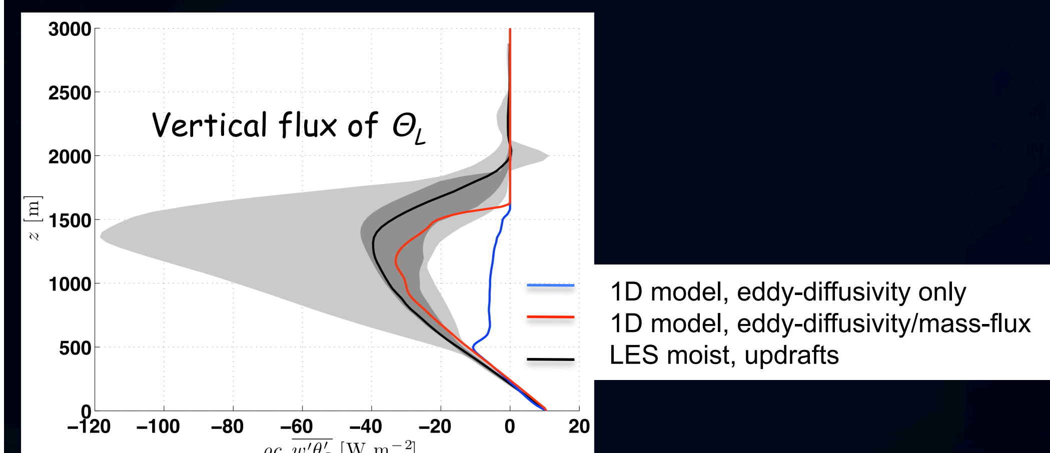
Results – Cumulus convection

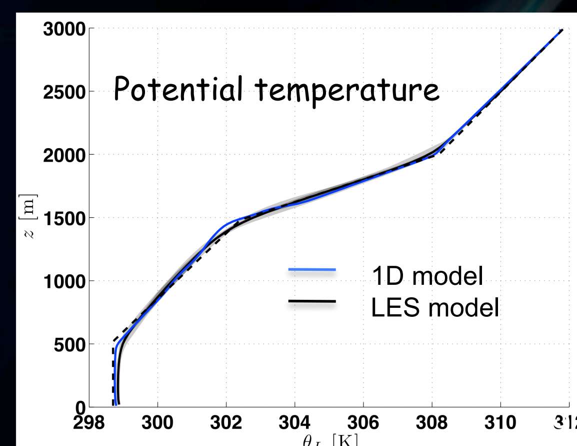
Offline testing of the updraft routine – BOMEX case (Siebesma et al., 2003) - comparison with LES results











Conclusions and further plans

- Combination of eddy-diffusivity and mass-flux is a promising parameterization approach for convective boundary layers
- Stratocumulus and cumulus cases can be well simulated

- Simulation stratocumulus to cumulus transition
- Extension to precipitating convection
- Implementation and testing of parameterization in NASA GEOS5 model

Thank you for your attention